Cascading Surge-Protective Devices: Options for Effective Implementations

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Significance
Part 8 – Coordination of cascaded SPDs

The early nineties were marked by the emergence of concerns about the coordination of cascaded SPD as the concept of “Whole-house protection” was gaining popularity. However, it appeared that the selection of service entrance SPDs and point-of-use plug-in SPDs was not an integrated process, hence some possibility that the expected coordination might not be achieved. On the other hand, if a well-designed combination could be implemented by a single authority responsible for the selection of the two devices, then the competing requirements for these to devices might be accommodated.

The service entrance SPD is generally selected from the point of view of the utility, and therefore tends to be a rugged device with relatively high limiting voltage because of the desire to have a conservative maximum continuous operating voltage (MCOV). On the other hand, the point-of-use SPDs, for those purchased independently from the service entrance SPD, are generally designed to offer the lowest possible limiting voltage. This relationship makes coordination difficult. If the two devices are selected with the same limiting voltage (and thus comparable MCOVs), then the inductance separating the two devices can have a chance to decouple the two devices sufficiently to achieve a satisfactory coordination. The inductance of the wiring between the service entrance can add some voltage drop between the two devices, so that an acceptable degree of coordination can still be achieved if the two device have equal limiting voltages. The redeeming effect of the wiring inductance is of course dependent upon the waveform of the impinging ***current surge***, as well as the length of the branch circuit.

In this paper, the relationships of these parameters are explored by numerical simulations. Cross-validation of simulation and measurements in actual circuits for typical applied surges was demonstrated in earlier papers so it was not repeated here.

CASCADING SURGE-PROTECTIVE DEVICES: OPTIONS FOR EFFECTIVE IMPLEMENTATIONS

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Abstract — The basic and critical parameters for a successful coordination of cascaded surge-protective devices include the relative voltage clamping of the two devices, their electrical separation through wiring inductance, and the actual waveform of the impinging surge. The authors examine in detail the implications of the situation resulting from the present uncoordinated application of devices with low clamping voltage at the end of branch circuits and devices with higher clamping voltage at the service entrance. As an alternative, several options are offered for discussion, that might result in effective, reliable implementation of the cascaded protection concept.

INTRODUCTION

Coordinating cascading surge-protective devices is a concept whereby two devices are connected at two different points of a power system, with some physical, but mostly electrical, separation (inductance) between the two points. The upstream device is designed to divert the bulk of an impinging surge, while the downstream device, close to the equipment to be protected, is intended as a final clamping stage, including surges generated within the facility.

Successful coordination is achieved when the heavy-duty upstream device does indeed divert the bulk of the surge, rather than letting the downstream device attempt to divert an excessive amount of the surge current. To distinguish between the two surge-protective devices (abbreviated as 'SPD'), the heavy-duty, upstream device will be referred to as 'arrester', while the lighter duty, downstream device will be referred to as 'suppressor'. The basic and critical parameters for successful coordination of the arrester-suppressor cascade include the relative voltage clamping of the two devices, their electrical separation through wiring inductance, and the actual waveform of the impinging surge.

The prime objective of a cascade arrangement is to maximize the benefit of surge protection with a minimum expenditure of hardware. Another benefit of a cascade is the diversion of large surge currents at the service entrance, so that they do not flow in the building, thereby avoiding side effects (Martzloff, 1990).*

The idea of a two-step protection has been explored by many authors over the last two decades, as can be seen in the bibliography included in this paper. Starting with different premises, and with changing opportunities as the technology evolved, these authors have reached conclusions that are sometimes convergent, and sometimes divergent, giving the appearance of contradictions.

In two previous papers (Lai & Martzloff, 1991; Martzloff & Lai, 1991), we have examined the simple case of a two-wire, single-phase circuit where each of the two SPDs is connected between the high-side of the line and the low-side (neutral or grounding conductor), showing by numerical examples the effect of three significant parameters: relative clamping voltage, separation, and impinging waveform. When these three parameters are all taken into consideration, many of those earlier divergent conclusions no longer appear contradictory. Rather, they become for each case a limited view of a consistent set that changes over the complete matrix of the possible ranges for the three parameters.

The two-wire circuit is a simplification applicable to the U.S. practice for residential service, which is generally single-phase, with a mid-point neutral bonded to the local ground at the entrance to the building. In some countries, a notable difference exists in the practice of grounding: the neutral is grounded at the distribution transformer but is not grounded at the service entrance as well. Instead, the installation includes a distinct 'protective-earth' conductor that is bonded to the local earth ('ground' in U.S. English), not to the neutral. In contrast, U.S. practice is to bond to local ground, at the service panel, both the neutral and the 'equipment grounding conductor' that serves the same protective function as the 'protective earth' in European practice.

This difference in the utility grounding practice has implications on the implementation of a cascade in the European context, where a service entrance arrester is more likely to be connected between the incoming lines and protective earth, while end-of-circuit suppressors are more likely to be connected between line and neutral. This arrangement is more complex than the simple two-wire cascade corresponding to the U.S. practice, and we propose a model that takes into consideration this more complex circuit. In the unbonded neutral connection scheme, there is a greater separation between the two cascaded devices and thereby the likelihood of successful coordination can be expected to increase.

** Citations are presented as (Author, Date) rather than as numbered items, and are listed alphabetically in the appended bibliography. The bibliography also includes items not cited in this paper, as an indication of the increasing level of interest in this subject.*

† Technology Administration, U.S. Department of Commerce

It is one thing to design an approach based on optimum coordination where all the parameters are under the control of the designer. Such an opportunity existed in utility systems implemented under centralized engineering. It is an altogether different challenge to attempt, after the fact, coordinating the operation of surge-protective devices connected to the power system by diverse and uncoordinated (and uninformed) users. For example, excessively low clamping voltages may be a threat to long-term reliability of varistors (Martzloff & Leedy, 1987; Davidson, 1991).

Our effort in promoting a coordinated approach may come too late for the de facto situation of having millions of suppressors in service with a relatively low clamping voltage. This situation will impose an upper limit to the clamping voltage of a candidate retrofitted arrester. Therefore, close attention must be paid to the selection of the relative clamping voltage of the two devices, in view of the conflicting requirements for performance under surge conditions — a successful cascade — and reliable withstand for temporary power-frequency overvoltages. Nevertheless, coordination might still be achieved through understanding the possible tradeoffs; in the future, users could avoid the pitfalls of poor coordination or the disappointment of implementing protection schemes that cannot provide the hoped-for results.

Finally, we propose for discussion among utilities and manufacturers a different approach to the selection of the service entrance arrester: a one-shot expendable device that would protect the installation against rare, but catastrophic sustained temporary overvoltages at power frequency.

THE RELATIVE VOLTAGE PARAMETER

Figures 1 and 2, from (Martzloff & Lai, 1991), illustrate the impact of the relative voltages on the energy sharing between the two devices. In these two figures, a plot is shown of the percentage of the total energy dissipated in the suppressor, as a function of the distance separating the two devices, for various combinations of clamping voltages, and for two postulated waveforms. In the plots, H, M, and L correspond respectively to a high, medium, and low voltage rating, in the context of a 120-V rms circuit application.

As long as the only postulated impinging waveform remained the classical 8/20-μs current surge (Figure 1), good coordination could be expected, even with an arrester clamping at a voltage somewhat higher than the clamping voltage of the suppressor. That philosophy was espoused in the development of several insulation coordination documents of the International Electrotechnical Commission (IEC) in the last decade (Crouch & Martzloff, 1978; Martzloff, 1980; IEC 28A[USA/Las Vegas]09, 1983 and its later modifications).

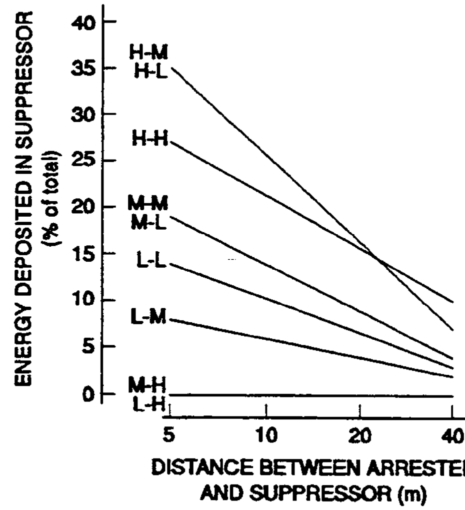


Figure 1
Relative energy deposited by a 3-kA, 8/20-μs wave in the suppressor for arrester-suppressor combinations of 250 V (H), 150 V (M), or 130 V (L) ratings, as a function of separation distance

However, if, in accordance with new descriptions of the surge environment, we apply a surge with longer waveform, such as the 10/1000 μs of ANSI/IEEE C62.41-1991, or the German 10/350 μs (Hasse et al., 1989), then coordination cannot be obtained if the arrester has a higher clamping voltage than that of the suppressor (Figure 2).

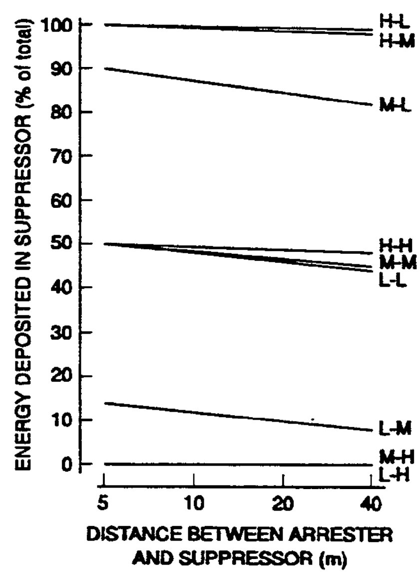


Figure 2
Relative energy deposited by a 220-A, 10/1000-μs wave in the suppressor for arrester-suppressor combinations of 250 V (H), 150 V (M), or 130 V (L) ratings, as a function of separation distance

A partial remedy might be expected in a scenario where the arrester and the suppressor would be specified with the same nominal (rms) voltage. The arrester would have, by definition, a larger cross-section than the suppressor, in order to fulfill its mission of prime dissipator of energy. The larger cross-section results in a lower current density, lowering the clamping voltage compared with that developed for the same current into the suppressor experiencing a higher current density. Thus, we could expect some relief of the 50%-50% division of energy shown in Figure 2 for two devices of equal voltage rating.

To quantify this expectation, we have modeled a 40-mm diameter varistor rated 150 V rms, and used the model defined in our 1991 paper for a 20-mm diameter varistor. Figure 3 shows the I-V characteristics for the two devices. Starting with the same voltage at 1 mA (equal by definition of the nominal voltage), the 40-mm varistor indeed provides a slightly lower clamping voltage than the 20-mm varistor, for currents above 1 mA. Conversely, for the same voltage (parallel connection), the plots show that in the 200-A range (the value selected for the 10/1000-μs wave in the 1991 tests), there is a 200/300 ratio in the currents flowing in the two devices. In the 3-kA range (the value shown in ANSI/IEEE C62.41 for the 8/20-μs wave), the 2000/3000 ratio is practically the same.

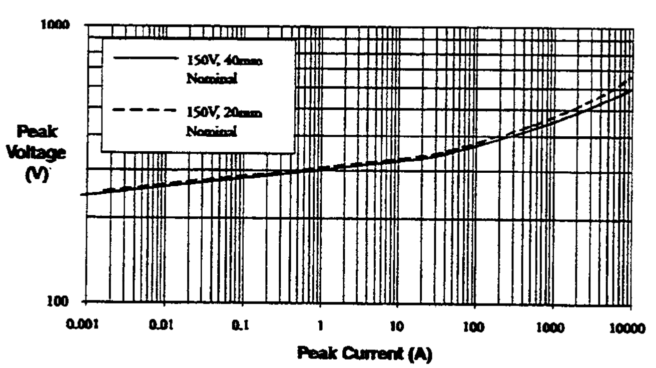


Figure 3
Curve-fitting for the nominal I-V characteristics of 150-V rated varistors, with diameters of 20 and 40 mm

This unequal sharing of the current for two parallel-connected devices with vertically offset characteristics is generally viewed as an obstacle to satisfactory operation, when the objective is to increase the energy handling capability of the two devices connected at the same point. In the present case, however, the objective is opposite: a very unequal sharing is sought to effect coordination between the two devices.

Figure 4 shows a cascade using the 40-mm varistor as service entrance arrester and the 20-mm varistor as surge suppressor. The figure also shows the concepts of location categories (A and B) defined in ANSI/IEEE C62.41-1991.

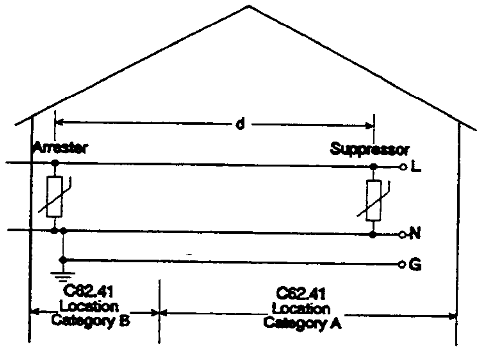


Figure 4
Configuration of a two-stage cascade, with both devices connected between line and neutral conductors

The arrester and the varistor are separated by a distance d, justifying the transition from Category B at the service entrance to Category A at the receptacle.

In the numerical examples and computer-generated plots illustrated below, we selected only one value, 10 meters, for the distance separating the arrester and the suppressor. In our referenced 1991 papers, we gave examples of distances ranging from 5 to 40 meters, as well as plots from measurements of the surge currents in an actual circuit. The correspondence between the modeling results and the experimental measurements was demonstrated in these papers. Therefore, for the similar combination of devices discussed here, we can use the same numerical model (with appropriate modification of the device parameters), and thus limit ourselves to modeling — precisely the point of having developed a valid model.

Figure 5 shows the computed current division between arrester (I_1) and suppressor (I_2) for a 3-kA, 8/20-μs wave impinging upon a cascade of two varistors, 40 mm for the arrester and 20 mm for the suppressor, each rated 150 V. Figure 6 shows the division for the same cascade with a 220-A, 10/1000-μs impinging wave.

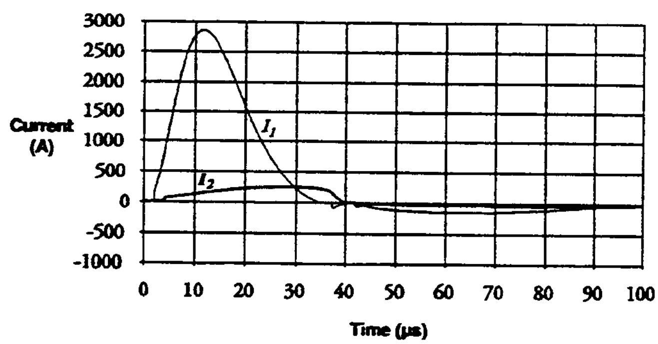


Figure 5
Division of the current between arrester (I_1) and suppressor (I_2) for a 150-V, 40-mm/20-mm cascade, 10-m separation, with a 3-kA, 8/20-μs impinging surge

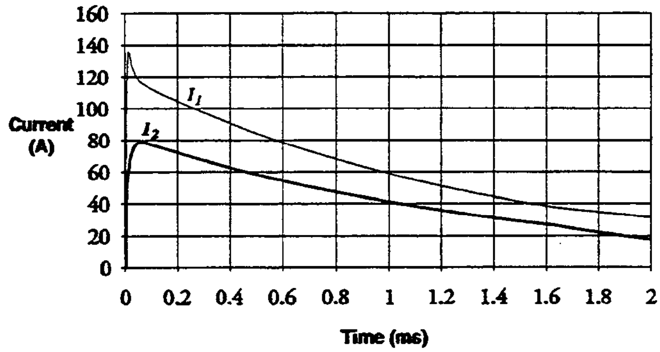


Figure 6
Division of the current between arrester (I_1) and suppressor (I_2) for a 150-V, 40-mm/20-mm cascade, 10 m separation, 220-A, 10/1000-μs impinging surge

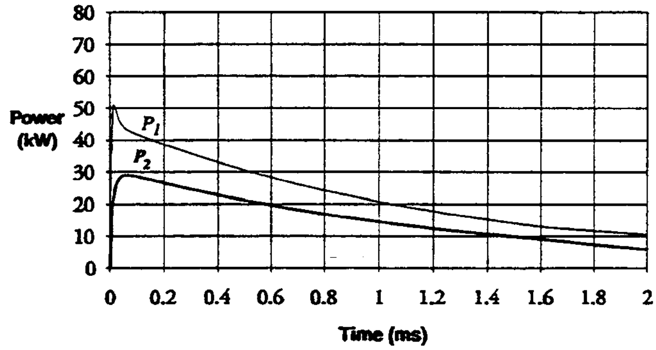


Figure 8
Division of the power between arrester (P_1) and suppressor (P_2) for a 150-V, 40-mm/20-mm cascade, 10 m separation, with a 220-A, 10/1000-μs impinging surge

Inspection of these two figures also provides qualitative insight on the behavior of the circuit. For the 8/20-μs wave, the inductance of the 10-m length of wire retards the rise of current in the suppressor during the first part of the surge, but tends to maintain the current in the suppressor even after the arrester current has decayed to zero. For the 10/1000-μs wave, the wiring contributes a significant difference in the currents only during the rapidly-changing period — the front of the wave — with the difference in the tail solely attributable to the difference in cross-section between the arrester and the suppressor.

Because of the quasi-constant voltage across the varistor during the surge event, the same behavior appears in the power plots of Figures 7 and 8 which show the power dissipated in each device, respectively for the 8/20-μs surge and the 10/1000-μs surge. The corresponding energy was obtained by integrating the two power curves. The results are shown in Table 1, which also includes the results for the original 20-mm/20-mm cascade.

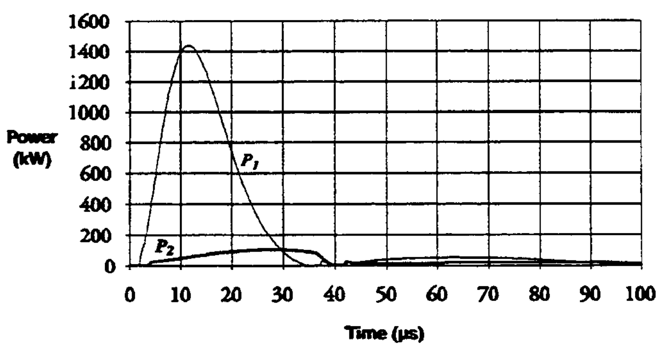


Figure 7
Division of the power between arrester (P_1) and suppressor (P_2) for a 150-V, 40-mm/20-mm cascade, 10 m separation, 3-kA, 8/20-μs impinging surge

Table 1
Distribution of deposited energy in arrester and suppressor, 20-mm/20-mm and 40-mm/20-mm cascades, 10 m separation, 8/20-μs and 10/1000-μs impinging surges

Waveform	Devices	Arrester (joules)	Suppressor (joules)	Suppressor (% of total)
8/20 μs 3 kA	20-20	23	3	12
	40-20	23	3	12
10/1000 μs 220 A	20-20	45	42	48
	40-20	46	31	40

Predictably, the 8/20-μs waveform produces a good coordination, for a 20-mm/20-mm cascade as well as for a 40-mm/20-mm cascade. In fact, the only difference between the two is a fraction of joule, which is not shown in the table where the values have been rounded off.

When postulating a 10/1000-μs waveform, the 40-mm arrester indeed diverts slightly more current than the 20-mm suppressor, as shown in Figure 6. However, when the energy levels are compared (see Table 1), the improvement obtained by changing from 20-mm/20-mm to 40-mm/20-mm cascades is only a small reduction in percentage of the total, down to 40% from the 48% of the original 20-mm/20-mm cascade.

The small 8% advantage of the 40-mm/20-mm cascade is likely to be lost when the statistics of possible tolerances for the two devices are considered. Figure 9 shows the effects of combining the relative tolerance deviations from nominal values, the same nominal values that were used in computing the advantage of the 40-mm/20-mm cascade over the 20-mm/20-mm cascade.

	Arrester High	Arrester Low
Suppressor High	8%	Increased
Suppressor Low	Decreased	8%

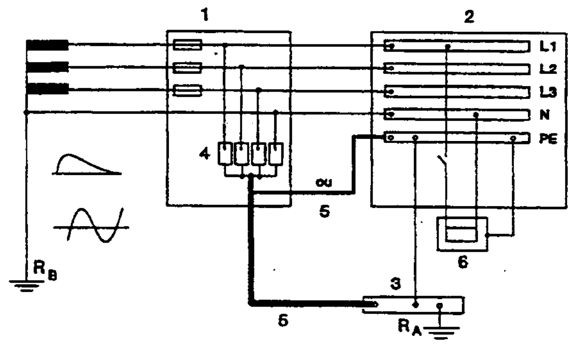
Figure 9
Advantage of 40-mm/20-mm cascade over 20-mm/20-mm cascade

For any cascade where the tolerances move in the same direction (50% of the cases), the advantage remains at 8%. For combinations where the tolerances make the arrester lower than the suppressor (25% of the cases), the advantage is improved. For combinations where the arrester is higher than the suppressor (25% of the cases), the advantage is decreased and may be completely wiped out. Thus, the hoped-for improvement from the lower current density might not be very substantial.

EFFECT OF GROUNDING PRACTICES

In polyphase systems, or even single-phase systems, the bonding between neutral and earth (ground) may be at some distance from the arrester — at the limit, one might consider a system with ungrounded neutral or no neutral. In such cases, the arresters are likely to be connected line-to-ground. Yet, the majority of suppressors are likely to be connected line-to neutral — the two conductors feeding the power port of the sensitive load in need of surge protection. Indeed, some countries or some suppliers object to any other mode of connection for surge-protective devices installed at receptacles or incorporated in connected equipment. Thus, the simple case treated in our 1991 papers, with the two devices (arrester and suppressor) diverting the surge to the same neutral conductor, may be more complicated — perhaps with the welcome effect of a greater separation of the two devices.

Figure 10, from (Roulet, 1992) shows a typical connection diagram for a three-phase system with a protective earth distinct from the neutral. This configuration could be modeled for the complete circuit; however, as an illustrative example and for comparison with the case of Figure 4, we have simplified the circuit as shown in Figure 11. The two varistors have the same voltage rating (150 V). Of course, in a European context of a 230/400-V three-phase system, the modeling should be done with varistors of appropriate ratings, say, 320 V. The generic conclusions reached for the example of the typical single-phase 240/120-V in use in the U.S. can be extended to the 230/400-V situation. We interpreted the configuration of Figure 10 and postulated for the coupling of the impinging surge as a common mode scenario, that is, a surge coupled by earth currents or by inductive coupling into the loop formed by all four conductors and earth.



Source: (Roulet, 1992)

LEGEND

RB: Earth ground at the distribution transformer
1: Service entrance panel
2: Sub-panel with feeders for branch circuits
3: Local earth electrode (PE)
4: Arresters connected to local earth (PE)
5: Connection of arresters to PE
6: Single-phase equipment that may contain an SPD

Figure 10
Typical three-phase installation with protective earth separate from the system neutral

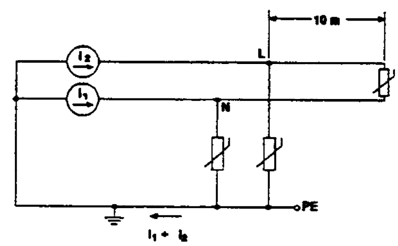


Figure 11
Simplified single-phase model derived from the three-phase system of Figure 10

Inspection of this circuit model reveals that separation between the two devices of the original cascade is no longer the simple length of two-conductor wire. The impinging surge, postulated to be common mode, must be revisited for such a power system configuration. If the two induced surge currents were exactly equal (the ideal common mode) and the two arresters were identical, the voltages produced at points L and N by the surge current flowing in each of the arresters would be equal. Thus, there would be no stress imposed upon the suppressor connected line-to-neutral at the end of the branch circuit.

For a voltage to appear between L and N, we must postulate unbalanced currents in the conductors L and N and a tolerance combination difference between the two arresters. Using this simplified model, we then computed the currents, powers, and energy depositions in a cascade consisting of two 40-mm varistors for the arresters, and a 20-mm varistor for the suppressor, both rated 150 V. We postulated a tolerance of +10% for the line arrester and a tolerance of -10% for the neutral arrester. For the current imbalance, we postulated respectively 3 kA and 1 kA for the case of an 8/20-μs impinging surge, and respectively 200 A and 100 A for a 10/1000-μs surge.

Figure 12 and Figure 13 show respectively the current distributions among the three devices for these two impinging surge waveforms. Even with the wide range of postulated differences between the arresters, the current in the suppressor is negligible.

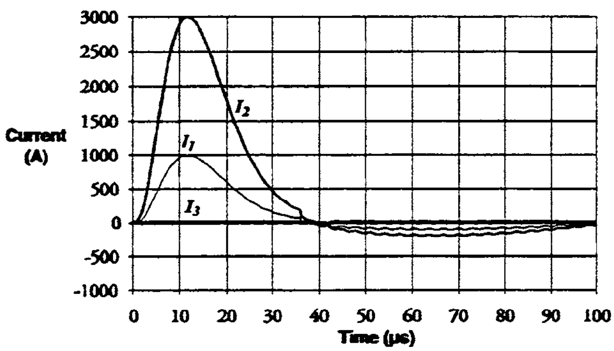


Figure 12
Division of the current among arresters (neutral, I_1), (line, I_2) and suppressor (I_3) for a 150-V cascade, 10-m separation, 1-kA/3-kA, 8/20-μs surge, and tolerances of +10% and -10% on the arresters

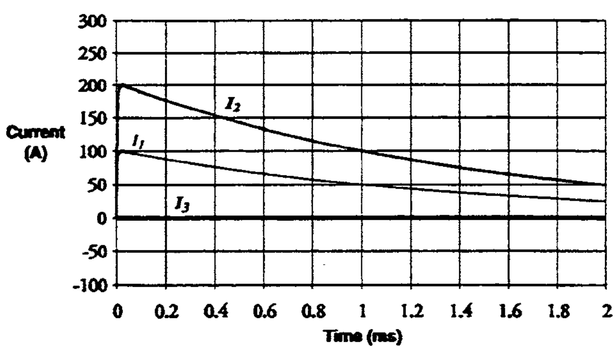


Figure 13
Division of the current among arresters (neutral, I_1), (line, I_2) and suppressor (I_3) for a 150-V cascade, 10-m separation, 100-A/200-A, 10/1000-μs surge, and tolerances of +10% and -10% on the arresters

Intuitive analysis of highly nonlinear varistor circuits can lead to severe errors. However, in this case, the results of the accurate numerical computations can be readily understood by recognizing that the difference in voltages at points N and L is only 20% of the arrester clamping voltages, too little to cause a significant current in the suppressor.

Thus, a marked difference in the cascade behavior occurs, depending upon the neutral earthing practice of the utility and the corresponding postulated scenario for coupling the impinging surge. It is important to note that we have presented only two possible configurations among the many that may be encountered for different countries. Therefore, correct application of surge-protective devices will be achieved only through a good understanding of the context — the grounding practices — of a particular application. Such an understanding will require coordination of the application information now being developed in several Technical Committees or Subcommittees of the International Electrotechnical Commission (IEC), specifically SC28A (Insulation Coordination), SC37A (Low-Voltage Surge-Protective Devices), 64 (Installation Wiring), SC77B (High-Frequency Disturbances), and 81 (Lightning Protection).

SERVICE ENTRANCE ARRESTER OPTIONS

Among electric utilities, different philosophies and different standards are encountered on what is deemed to be an acceptable temporary overvoltage level. For instance, in the U.S., ANSI Std C84.1-1989 only cites a moderate allowance for temporary overvoltages (+6% for 'Range B') but acknowledges the possibility for greater overvoltages to occur, in which case "prompt corrective action shall be taken." The French utility* considers that temporary (over 5 seconds) overvoltages of 1.5 times the nominal system voltage must be accepted as a realistic, unavoidable level in their distribution systems. Some utilities may even wish to have a service entrance arrester survive the condition of a loose neutral connection in a three-wire, neutral bonded to center-tap system, where overvoltages on the lightly-loaded side can reach values up to almost twice the nominal system voltage.

The occurrence of a temporary (seconds) overvoltage of 1.5 per-unit, or more, is likely to cause massive failure of consumer-type equipment in a residence, raising the issue of liability of the utility for this failure, in view of the European trends in legislating that 'electricity is a product' and that suppliers thereof are liable in the case of a defective product.

* Communication by J.P. Meyer at *UTE Workshop on Surge Arresters*, Paris, March 20, 1992.

An effective solution to this problem might be to design the service entrance arrester in such a manner that its relatively low maximum continuous operating voltage (made necessary by the millions of low-rated suppressors) will cause it to fail — *in an acceptable short-circuit mode* — and thereby protect the equipment within the residence. Service would be interrupted and a replacement of the one-shot, expendable arrester would be required, but the consequential liability of massive appliance failures would be avoided. This option seems to merit careful examination by the electric utilities, the arrester manufacturers, and the standards- or code-writing bodies.

THE DILEMMA OF SPD VOLTAGE RATINGS

The foregoing results, added to those presented in the many papers cited in the bibliography, forebode quite a challenging task of coordinating a cascade downstream of the service entrance. This challenge is made even more difficult by including the concerns about the 'Low-Side Surges' that have led to the recommendation of service-entrance arresters with ac rms ratings higher than the classic 175 V (Dugan & Smith, 1986; Dugan, Kershaw & Smith, 1989; Marz & Mendis, 1992).

Caught between the inescapable, too-late-to-be-changed situation of the 130-V varistors embedded in appliances and the recommendation of 175 V or more for arresters at the service entrance, the coordination schemes proposed by different authors appear elusive: equal voltages (Huse, Martzloff), lower voltage for the entrance (Hasse et al., Standler, Hostfet et al.), or slightly higher arrester voltage (Stringfellow). Perhaps, the 1970s-vintage protection schemes, with a gap-type arrester (Martzloff, 1980), rekindled as a result of the new coordination issues (Hasse et al., 1989), might be another solution. From the diverse interests and expertise of the five IEC committees mentioned above, a solution might emerge, although it is not obvious at this time.

CONCLUSIONS

1. The reality of having many millions of 130-V rated varistors installed on 120-V systems, and 250-V rated varistors installed on 230-V systems makes the ideal scenario of a well-coordinated cascade difficult or perhaps unattainable in the near future.

2. As a compromise, a cascade with equal voltage ratings for the arrester and the suppressor can offer successful coordination, if the impinging surges are presumed to be relatively short.

3. The coordination of a simple cascade of an arrester and a suppressor of equal voltage rating, both connected line-to-neutral, is slightly improved by the larger cross-section of the arrester. However, an unfavorable combination of tolerances for the two devices can wipe out the improvement.

4. The neutral grounding practice of the utility has a profound effect on the cascade behavior, and must be thoroughly understood for successful application of cascaded surge protection. Clearly, additional studies are required in this area.

5. The waveform of the impinging surge has also a large effect on the outcome. If more data were available on the frequency of occurrence of 'long surges', some of the uncertainty surrounding the success of a cascade would be lifted.

6. The idea of an expendable, one-shot arrester at the service entrance could offer a solution out of the dilemma and should be further investigated.

Jih-Sheng (Jason) Lai *is a native of Taiwan. He received his M.S. and Ph.D. in electrical engineering from the University of Tennessee, Knoxville, in 1985 and 1989, respectively. From 1980 to 1983, he was the Electrical Engineering Department Chairman of Ming-Chi Institute of Technology, Taipei, Taiwan, where he initiated a power electronic program and received a grant from the school and the National Science Council to study abroad.*

In 1989, he joined the EPRI Power Electronics Applications Center, where he is currently the Power Electronics Manager. His main research interests are power electronics modeling and simulation, circuit design, and microcomputer applications. Dr. Lai has 2 patents in high frequency power conversions for adjustable speed drives and more than 25 articles published in the fields of control systems, power systems, and power electronics. In the surge protection area, he developed varistor models and simulated cascaded surge protection circuits to understand more about fundamental concepts.

François D. Martzloff *is a native of France. After undergraduate studies there, he obtained an M.S., E.E. at Georgia Tech in 1952 and, twenty years later, an M.S., I.A. at Union College. After 32 years in the private sector (Southern States Equipment, 1953-1956, and GE, 1956-1985), he joined the National Bureau of Standards, now National Institute of Standards and Technology. His early professional experience included the design of high-voltage fuses and high-voltage bushings. He changed to semiconductor technology, but his high-voltage experience led him to the study of transients, which he has steadily pursued for the last 30 years.*

As an IEEE Fellow, he has contributed a number of papers and led the development of several standards on surge characterization and surge testing. He has been granted 13 patents, mostly on surge protection. In the IEC, he is serving as Convenor of two working groups and chairs Subcommittee 77B (High-frequency Disturbances) of TC77 on Electromagnetic Compatibility (EMC).

APPENDIX — BIBLIOGRAPHY *

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* *The authors and the concerned IEC Working Groups would welcome contributions of additions to this bibliography.*